CHAPTER 2: ATOMS, IONS, AND MOLECULES

Problems: 2.1-2.78, 2.81-2.93, 2.94-2.96, 2.111-2.119, 2.121, 2.127

2.1 THE NUCLEAR MODEL OF ATOMIC STRUCTURE

Joseph John (J. J.) Thomson (1897) carried out experiments with cathode rays.
- His research group determined the charge-to-mass ratio of the particles in the rays.
- They determined the particles were composed of tiny, negatively charged subatomic particles → electrons (e−)

Eugen Goldstein (late 1880s)
- Discovered canal (or anode) rays which were composed of positively charged subatomic particles → protons (p+)

And decades later, James Chadwick won the Nobel Prize winner for his discovery (1935) → neutron (n) = neutral subatomic particle

PLUM-PUDDING MODEL OF THE ATOM
- Thomson proposed that the atom was a uniform sphere of positively charged matter in which electrons were embedded → electrons are like raisins in a pudding of protons

THE NUCLEAR ATOM: PROTONS AND THE NUCLEUS
- Ernest Rutherford was a scientist who did many pioneering experiments in radioactivity
- He had members of his research group test Thomson’s Plum-Pudding Model using radioactive alpha (α) particles, basically helium atoms with a +2 charge and much bigger than an electron.

Rutherford’s Alpha-Scattering Experiment
- Alpha (α) particles shot at a thin gold foil that’s only a few atoms thick
- A circular detector is set up around the foil to determine what happens to the α particles.
- If Plum-pudding Model was correct, the α particles should go through the foil like bullets through tissue paper.

Experimental results:
- Most of the α particles went straight through, but some were deflected or even bounced back!
Consider what the scientists expected to observe given each model:

Rutherford’s interpretation of the results
- Most alpha (α) particles pass through foil
  - Atom is mostly empty space with electrons moving around the space
- Some α are deflected or bounce back
  - Atom must also contain a dense region, and particles hitting this region are deflected or bounce back towards source.
  - dense region = atomic nucleus (contains atom’s protons and neutrons)
  - Why this is called the NUCLEAR Model of the Atom

Rutherford also estimated the size of the atom and its nucleus:

Ex. 1: An atom is 100,000 times (10^6 or 5 orders of magnitude) bigger than its nucleus.
If a nucleus = size of a small marble (~1 cm in diameter), indicate the length in meters then identify a common item that corresponds to that size for the following:

a. 10 times bigger = ___________ m = ______________________

b. 100 times bigger = __________ m = ______________________

c. 1000 times bigger = __________ m = ______________________

d. 10,000 times bigger = __________ m = ______________________

e. 100,000 times bigger = __________ m = ______________________
Properties of Protons, Neutrons, and Electrons

<table>
<thead>
<tr>
<th>Subatomic Particle</th>
<th>Charge</th>
<th>Location</th>
<th>Mass (amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>+1</td>
<td>inside nucleus</td>
<td>1.00728</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>inside nucleus</td>
<td>1.00866</td>
</tr>
<tr>
<td>Electron</td>
<td>-1</td>
<td>outside nucleus</td>
<td>0.00055</td>
</tr>
</tbody>
</table>

2.2 ISOTOPES

Each element always has the same number of protons, but the number of neutrons may vary. Atoms with different numbers of neutrons are called *isotopes.*

- e.g. Carbon exists as carbon-12, carbon-13, and carbon-14 where each carbon atom has 6 protons but 6, 7, or 8 neutrons respectively
- Isotopes are identified with an element name followed by the mass number
  - e.g. uranium-235 (U-235), carbon-12 (C-12), cobalt-60 (Co-60), etc.

**Atomic Notation:**

- shorthand for keeping track of number of protons and neutrons in the nucleus
  
  - atomic number (Z): whole number of \( p^+ \)= number of \( e^- \) in neutral atom
  - mass number (A): whole number sum of *protons and neutrons* in an atom
    - Note electrons contribute almost no mass to an atom

\[
\text{Mass number}=A
\]
\[
\text{Atomic number}=Z
\]

Complete the following table:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass number</th>
<th># of protons</th>
<th># of neutrons</th>
<th># of electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>strontium-86</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{92}\text{Mo})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>zinc-72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{136}\text{Ba}^{2+})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{31}\text{P}^3-)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A review for section 2.3 Average Atomic Masses is available on the Chapter 2 Review from our class Website.
2.4 THE PERIODIC TABLE OF THE ELEMENTS

METALS, NONMETALS, & SEMIMETALS

Know which elements are metals, semimetals, nonmetals using the Periodic Table.

Properties of Metals
- shiny appearance
- conduct heat & electricity
- malleable: can be flattened into thin sheets
- ductile: can be stretched into a wire
- e.g. aluminum, copper, gold

Properties of Nonmetals
- dull appearance
- brittle
- nonconductor
- e.g. carbon (graphite in pencils), sulfur

Properties of Metalloids (or Semimetals): Have properties of metals and nonmetals
  – For example, silicon is shiny like a metal and acts as a semiconductor.
SOLIDS, LIQUIDS, AND GASES: KNOW the physical state of each element at 25°C!

At standard state conditions (25°C and 1 atm):
- Only mercury (Hg) and bromine (Br) are liquid
- H, N, O, F, Cl, and all Noble gases (group VIIA) are gases
- All other elements are solids

2.5 TRENDS IN COMPOUND FORMATION

chemical bond: what holds atoms or ions together in a compound

COVALENT BOND and MOLECULES
- 1st type of chemical bond: Covalent Bond
  - covalent bond: sharing of a pair of electrons by 2 nonmetal atoms
  - Two or more covalently bonded atoms form a molecule (or molecular compound)

molecule: basic unit of a compound of covalently bonded atoms
- Consider the HCl, H₂O, NH₃, and CH₄ molecules below
  - Note how the chemical formula gives the actual number of each atom present in the following compounds:
Diatomic Molecules:
- Recognize these elements that exist as diatomic molecules ($X_2$):
  \[ \text{H}_2 \quad \text{N}_2 \quad \text{O}_2 \quad \text{F}_2 \quad \text{Cl}_2 \quad \text{Br}_2 \quad \text{I}_2 \]
- Consider these the “diatomic seven” since there are seven of them, and six of them form a 7 on the periodic table.

IONS
- When atoms lose or gain electrons, they form charged particles called ions.
  - Metals lose electrons $\rightarrow$ positively charged ions = cations
  - Nonmetals gain electrons $\rightarrow$ negatively charged ions = anions

Main-group elements generally form ions—i.e. gain or lose electrons—to get the same number of electrons as a Noble gas.
$\rightarrow$ Ions formed by main-group elements are usually isoelectronic with—i.e., have the same number of electrons as—one of the noble gases!

Ions formed by Main-Group Elements (charges are shown as superscripts):
- Group IA elements $\rightarrow$ +1 charge: Li$^+$, Na$^+$, K$^+$, etc. (“+” = “+1”)
- Group IIA elements $\rightarrow$ +2 charge: Mg$^{2+}$, Ca$^{2+}$, Sr$^{2+}$, Ba$^{2+}$, etc.
- Group IIIA elements $\rightarrow$ +3 charge: Al$^{3+}$
- Group VA elements $\rightarrow$ -3 charge: N$^{3-}$, P$^{3-}$
- Group VIA elements $\rightarrow$ -2 charge: O$^{2-}$, S$^{2-}$, Se$^{2-}$
- Group VIIA elements $\rightarrow$ -1 charge: F$^-$, Cl$^-$, Br$^-$, I$^-$, etc.

IONIC BONDS and IONIC COMPOUNDS
- 2nd type of chemical bond: IONIC BOND
  - Ions in an ionic compound are held together by ionic bonds.
  - Ionic bond: electrostatic attraction holding together positively charged metal cations and negatively charged nonmetal anions
**formula unit:** most basic entity of an ionic compound (eg. NaCl, Al₂O₃, etc.)

- The formula gives the ratio of ions (not actual #).
- The 3D representation of NaCl at the right shows a network of Na⁺ (purple) and Cl⁻ ions (green).
- The formula, NaCl, indicates a 1-to-1 ratio of Na⁺ ions and Cl⁻ ions present, not the presence of only one ion of each.

An ionic compound is a network of ions, with each cation surrounded by anions, and vice versa.

→ To melt the solid, these bonds must be broken!

→ Ionic compounds have very high melting points compared to molecules like water.

### 2.6 NAMING COMPOUNDS AND WRITING FORMULAS

Every element can be identified using a name, symbol, or atomic number.

Know the names and symbols for the first 18 elements on the Periodic Table as well as those elements included in Figure 2.17 on p. 57, and uranium (U). The Periodic Table that will be given on quizzes and exams will include only the element symbols, atomic number, and atomic mass. Spelling counts!

#### IONIC COMPOUNDS

**CATIONS:** positively charged ions

- Metal atoms lose valence electrons to form cations.

I. Groups IA, IIA, IIIA elements, silver, zinc and cadmium form only one type of ion each.

- Group IA elements → +1 charge always (e.g. Li⁺=lithium ion)
- Group IIA elements → +2 charge always (e.g. Mg²⁺=magnesium ion)
- Group IIIA elements → +3 charge always (e.g. Al³⁺=aluminum ion)
- Silver ion = Ag⁺; zinc ion = Zn²⁺; cadmium ion = Cd²⁺

II. The Stock system is used to name transition metals, Pb, and Sn forming different charges.

- e.g. iron (Fe), a transition metal, forms 2 different ions: Fe²⁺ and Fe³⁺
- e.g. lead (Pb), in Group IVA, forms 2 different ions: Pb²⁺ and Pb⁴⁺

When a metal can form more than one ion, each ion is named:

<table>
<thead>
<tr>
<th>Element</th>
<th>Charge in Roman Numerals</th>
<th>Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb²⁺</td>
<td>lead (II) ion</td>
<td></td>
</tr>
<tr>
<td>Pb⁴⁺</td>
<td>lead (IV) ion</td>
<td></td>
</tr>
<tr>
<td>Cu⁺</td>
<td>copper (I) ion</td>
<td></td>
</tr>
<tr>
<td>Cu²⁺</td>
<td>copper (II) ion</td>
<td></td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>iron (II) ion</td>
<td></td>
</tr>
<tr>
<td>Fe³⁺</td>
<td>iron (III) ion</td>
<td></td>
</tr>
</tbody>
</table>
ANIONS: formed only by nonmetals
– When a nonmetal forms an ion, it is named:

\[
\text{element stem name} + \text{-ide suffix} + \text{ ion}
\]

\[
\begin{align*}
O &= \text{oxygen atom} \quad \rightarrow \quad O^{2-} = \text{oxide ion} \\
N &= \text{nitrogen atom} \quad \rightarrow \quad N^{3-} = \text{nitride ion}
\end{align*}
\]

POLYATOMIC IONS
– Know the formulas and names of the following polyatomic ions:

\[
\begin{align*}
\text{NH}_4^+ &= \text{ammonium ion} & \text{CrO}_4^{2-} &= \text{chromate ion} & \text{CO}_3^{2-} &= \text{carbonate ion} \\
\text{Hg}_2^{2+} &= \text{mercury (I) ion} & \text{Cr}_2\text{O}_7^{2-} &= \text{dichromate ion} & \text{HCO}_3^- &= \text{hydrogen carbonate ion} \\
\text{SO}_4^{2-} &= \text{sulfate ion} & \text{MnO}_4^- &= \text{permanganate ion} & \text{ClO}^- &= \text{hypochlorite ion} \\
\text{C}_2\text{H}_3\text{O}_2^- &= \text{acetate ion} & \text{NO}_3^- &= \text{nitrate ion} & \text{ClO}_2^- &= \text{chlorite ion} \\
\text{PO}_4^{3-} &= \text{phosphate ion} & \text{NO}_2^- &= \text{nitrite ion} & \text{ClO}_3^- &= \text{chlorate ion} \\
\text{CN}^- &= \text{cyanide ion} & \text{OH}^- &= \text{hydroxide ion} & \text{ClO}_4^- &= \text{perchlorate ion} \\
\text{SCN}^- &= \text{thiocyanate ion} & \text{O}_2^{2-} &= \text{peroxide ion}
\end{align*}
\]

Naming Ionic Compounds:
1. Get the individual ions for each compound
2. CATION NAME + ANION NAME, minus “ion” → Name of compound

Ex. \( \text{ZnS} = \)

\[
\begin{array}{cc}
\text{individual ions} & \text{name of compound} \\
\text{ex} & \\
\text{Fe}_2(\text{Cr}_2\text{O}_7)_3 = & \\
\text{CdF}_2 = & \\
\text{Ni(OH)}_3 = & \\
\text{Hg(ClO}_4)_2 = & \\
\text{Cu}_3(\text{PO}_4)_2 = & \\
\text{BaSO}_4 = & \\
\text{PbO}_2 = & \\
\text{K}_2\text{O}_2 = & \\
\end{array}
\]
Given the name of a compound, predict the formula:
- KNOWING charges on ions formed by representative elements!
- KNOWING how to use polyatomic ions and their charges when given to you!

aluminum cyanide: 
\[ \text{individual ions} \rightarrow \text{formula of compound} \]
copper(I) sulfide: 
copper(II) sulfide: 
barium chlorate: 
zinc phosphate: 
cobalt(III) chromate: 
silver nitrate: 
tin(II) permanganate: 
calcium carbonate: 

BINARY MOLECULAR COMPOUNDS: composed of 2 nonmetals

NAMING: # of atoms of element indicated by Greek prefix before element name
1. For first element, Greek prefix + element name
2. For second element, Greek prefix + element name stem + "ide"
   - If only one atom present, "mono-" is usually omitted, except for CO=carbon monoxide.

<table>
<thead>
<tr>
<th># of atoms</th>
<th>Greek prefix</th>
<th># of atoms</th>
<th>Greek prefix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mono</td>
<td>6</td>
<td>hexa</td>
</tr>
<tr>
<td>2</td>
<td>di</td>
<td>7</td>
<td>hepta</td>
</tr>
<tr>
<td>3</td>
<td>tri</td>
<td>8</td>
<td>octa</td>
</tr>
<tr>
<td>4</td>
<td>tetra</td>
<td>9</td>
<td>nona</td>
</tr>
<tr>
<td>5</td>
<td>penta</td>
<td>10</td>
<td>deca</td>
</tr>
</tbody>
</table>

Example: \( \text{CO}_2 = \text{carbon dioxide} \)

\( \text{CCl}_4 = \) \[ \] \( \text{SF}_6 = \) \[ \]
\( \text{P}_4\text{O}_{10} = \) \[ \] \( \text{Cl}_2\text{O}_3 = \) \[ \]
Some binary molecular compounds also have common names
- e.g. everyone knows (or should know) \( \text{H}_2\text{O} \) is water

**Other common compounds and names you must know:**

\[
\begin{align*}
\text{NH}_3 & = \text{ammonia} & \text{CH}_4 & = \text{methane} & \text{H}_2\text{O}_2 & = \text{hydrogen peroxide}
\end{align*}
\]

**ACIDS:** Aqueous solutions of a compound that releases \( \text{H}^+ \) ions
- usually have \( \text{H} \) in front, physical state indicated as aqueous (aq)
- naming depends on the ion from which the acid forms

\[
\begin{align*}
\text{F}^- & = \text{fluoride ion} & \text{add \# of H's equal to negative charge} & \rightarrow & \text{HF}(aq) & = \text{hydrofluoric acid} \\
\text{NO}_2^- & = \text{nitrile ion} & \text{add \# of H's equal to negative charge} & \rightarrow & \text{HNO}_2(aq) & = \text{nitrous acid} \\
\text{NO}_3^- & = \text{nitrile ion} & \text{add \# of H's equal to negative charge} & \rightarrow & \text{HNO}_3(aq) & = \text{nitrile acid}
\end{align*}
\]

For some acids, the stem name changes:

\[
\begin{align*}
\text{PO}_4^{3-} & = \text{phosphate ion} & \text{add \# of H's equal to negative charge} & \rightarrow & \text{H}_3\text{PO}_4(aq) & = \text{phosphoric acid}
\end{align*}
\]

**Exercises:**

\[
\begin{align*}
\text{Cl}^- & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________} \\
\text{CO}_3^{2-} & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________} \\
\text{SO}_3^{2-} & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________} \\
\text{C}_2\text{H}_3\text{O}_2^- & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________} \\
\text{Br}^- & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________} \\
\text{SO}_4^{2-} & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________} \\
\text{ClO}^- & = \text{________________} & \text{add \# of H's equal to negative charge} & \rightarrow \text{________________} = \text{________________}
\end{align*}
\]